Gamma Radiation from Magnesium-26 under Proton Bombardment*

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Thin targets of Mg^{26} were bombarded with protons from a Van de Graaff generator. Fifteen well-defined resonance peaks were found in the proton energy region between 300 and 1500 kev. These resonances were attributed to the reaction $Mg^{26}(p,\gamma)Al^{27}$. The maxima of the resonances occur at proton energies of 343, 450, 662, 720, 813, 840, 954, 992, 1015, 1056, 1172, 1255, 1295, 1425, and 1464 kev. Measurement of the gamma-ray energies from some of the stronger resonances indicate that the compound nuclei do not in most cases decay to the ground state by a single transition.

I. INTRODUCTION

IN 1939 Curran and Strothers[1] bombarded relatively thin targets of magnesium with protons having energies up to 1000 kev. Although their resolution was rather poor by modern standards, they detected several gamma-ray resonance peaks for protons in this energy region. The three proton capture reactions which are energetically possible in natural magnesium for protons of low (under 2 Mev) energy are:

$$(1)\quad Mg^{24}+H^1\rightarrow Al^{25*}\rightarrow Al^{25}+h\nu \searrow Mg^{25}+\beta^+,$$

$$(2)\quad Mg^{25}+H^1\rightarrow Al^{26*}\rightarrow Al^{26}+h\nu \searrow Mg^{26}+\beta^+,$$

$$(3)\quad Mg^{26}+H^1\rightarrow Al^{27*}\rightarrow Al^{27}+h\nu.$$

By measuring the positron yield as a function of proton energy as well as the gamma-ray yield, Curran and Strothers were able to assign gamma-ray resonances unaccompanied by positron activity to proton capture in Mg^{26}. All resonance peaks at which both gamma rays and positrons were emitted were attributed to proton capture in Mg^{25}, because the unstable isotope Al^{25} was unknown at that time and because all the half-life measurements for the positron activity gave values near to the one accepted for Al^{26}.

Hole, Holtzmark, and Tangen[2] bombarded thin targets of natural magnesium with protons in the energy region between 200 and 500 kev. Only gamma-ray resonances were measured and eight peaks were observed, all of which can now be shown to be associated with proton capture in Mg^{24} and Mg^{26}. In 1946 Tangen[3] restudied the proton capture reactions in this energy region with much improved techniques. He found several additional resonances and was able to assign each resonance to capture in the correct magnesium isotope. In particular, he reported resonances in Mg^{26} at proton energies of 290, 314, 336, 383, 430, 451, and 494 kev. In 1953 Hunt and Jones[4] observed and measured the half-widths of the $Mg^{26}(p,\gamma)$ resonances excited by protons with energies between 250 and 500 kev. They reported peaks at 314.8, 338.5, 389.4, 436.5, 454.2, and 484.0 kev.

A survey of the gamma-ray yield from proton capture in magnesium targets was made for proton energies between 700 and 1600 kev by Cooper, Taylor, Harris, and Grove.[5] They found a number of resonances, some of them overlapping. The availability of separated isotopes of magnesium suggested the possibiltiy of resolving the complex spectrum by proton bombardments of the separated isotopes. A substantial increase in yield could be expected for Mg^{25} and Mg^{26}, which are present in natural magnesium to the extent of 11.5 and 11.1 percent, respectively. Upon allocation by Isotopes Division of the Atomic Energy Commission, small quantities of highly enriched isotopes of magnesium were obtained from the Carbide and Carbon Chemicals Corporation, Oak Ridge National Laboratory. It is the purpose of this paper to report the data obtained by the proton bombardment of thin targets made from Mg^{26}. The results of bombardment of targets of Mg^{25} have been presented in an earlier paper.[6]

II. EXPERIMENTAL PROCEDURE

Fifty-five milligrams of enriched Mg^{26} were obtained in the form of magnesium oxide. The isotopes analysis indicated 95.91 percent Mg^{26}, 1.56 percent Mg^{25}, and 2.53 percent Mg^{24}. Thin targets were prepared from this sample by evaporation in a vacuum followed by condensation on tantalum backings. The preparation of the targets is described in more detail elsewhere.[7] The targets used for most of the data were 10 to 15 kev thick for one-Mev protons.

These targets were bombarded by protons which were separated from the ion beam of the electrostatic generator by a magnetic analyzer. The energy of the proton impinging on the target was determined by reading

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[1] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. (London) **A172**, 72 (1939).

[2] Hole, Holtzmark, and Tangen, Naturwiss. **28**, 399 (1940).

[3] R. Tangen, Kgl. Norske Videnskab. Selskabs, Forh. Skrifter No. 1. (1946).

[4] S. E. Hunt and W. M. Jones, Phys. Rev. **89**, 1283 (1953).

[5] Cooper, Taylor, Harris, and Grove, Phys. Rev. **80**, 131 (1950).

[6] Taylor, Russell and Cooper, Phys. Rev. **93**, 1056 (1954).

[7] Russell, Taylor, and Cooper, Revs. Sci. Instr. **23**, 764 (1952).

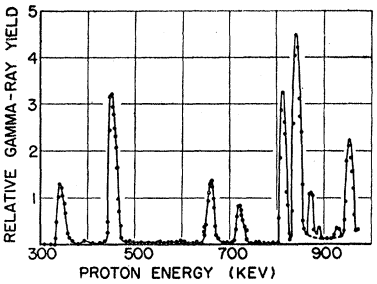

FIG. 1. The relative gamma-ray yield per incident proton from the $Mg^{26}(p,\gamma)Al^{27}$ reaction for protons with energies from 300 to 1000 kev. The peaks at 874, 890, and 935 kev are due to proton capture in a fluorine contamination in the target.

the current flowing in the coils of the analyzing magnet. This magnet current had been calibrated in terms of proton energy by use of the well-known resonance in lithium at 440 kev, and the resonances in fluorine at 486, 669, 873.5, 935.5, 1290, 1355, and 1381 kev as reported by Hornyak, Lauritsen, Morrison, and Fowler[8]

The target to be bombarded was placed at the end of a Faraday cage so that the charge carried by the proton beam could be determined. A thin-walled Geiger-Müller tube was used to detect the gamma rays emitted from the target. The gamma-ray yield per incident proton was then plotted as a function of the proton energy.

III. RESONANCES IN THE $Mg^{26}(p,\gamma)Al^{27}$ REACTION

The relative gamma-ray yield is shown as a function of the proton energy in Figs. 1 and 2. Figure 1 shows the proton energy region between 300 and 1000 kev, and Fig. 2 the region between 900 and 1600 kev. In this energy range there are fifteen resonance peaks attributed to proton capture in Mg^{26}. The proton energies corresponding to these resonance levels are 343, 450, 662, 720, 813, 840, 954, 992, 1015, 1056, 1172, 1255, 1295, 1425, and 1464 kev. The absolute energy value quoted for each of the fifteen resonance is probably correct within 10 kev, and the relative spacing

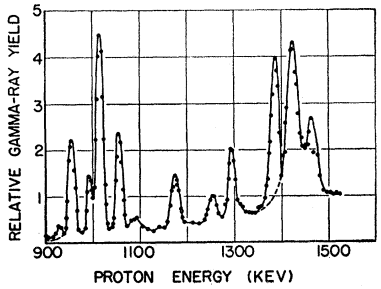

FIG. 2. The relative gamma-ray yield per incident proton from the $Mg^{26}(p,\gamma)Al^{27}$ reaction for protons with energies between 900 and 1600 kev. The peaks at 935 and 1379 kev are due to proton capture in a fluorine contamination in the target.

[8] Hornyak, Lauritsen, Morrison, and Fowler, Rev. Modern Phys. **22**, 291 (1950).

is believed to be right within 5 kev. The peaks at 343 and 450 kev agree with those reported by Tangen[3] and by Hunt and Jones[4] within the predicted errors. No effort was made to reexamine the very weak peaks under 500 kev which they reported.

In addition to the fifteen resonance peaks attributed to Mg^{26} there are shown resonances at 874, 890, 935, and 1379 kev which arise from proton capture in fluorine contamination on the target. These resonances are present in data taken with each of the three magnesium isotopes. The exact origin of this fluorine contamination is not certain.

The cross section of Mg^{26} for proton capture is low over the range of proton energies studied. Calculations for the 450-kev resonance indicate the cross section is approximately 5×10^{-27} cm^2.

IV. EXCITED STATES IN Al^{27}

The Q value for the $Mg^{26}(p,\gamma)Al^{27}$ reaction is 8.262 Mev according to the mass values presented by Li.[9] On the basis of this Q value the excitation levels in Al^{27} corresponding to the 15 proton resonance energies are listed in Table I.

TABLE I. Excitation levels in Al^{27} as determined by the proton energies at resonances.

Proton energy (kev)	Excitation energy (Mev)	Proton energy (kev)	Excitation energy (Mev)
343	8.592	1015	9.239
450	8.695	1056	9.278
662	8.899	1172	9.392
720	8.955	1255	9.471
813	9.046	1295	9.510
840	9.071	1425	9.634
954	9.180	1464	9.672
992	9.217		

In order to determine whether the excited Al^{27} nuclei went directly to the ground state by a single transition, efforts were made to measure the energy of the gamma rays emitted by two separate methods. The first method consisted of the measurement of the attenuation of the gamma rays in known thicknesses of lead and copper. The second method was the coincidence technique described by Fowler, Lauritsen, and Lauritsen.[10] Measurements were made at the 450, 813, 840, 954, and 1015-kev resonances and in every case the results indicated that the predominate mode of decay was not by a single transition to the ground state.

The indicated gamma-ray energies from resonance to resonance varied between 5.3 and 7.3 Mev. In view of the very large number[11,12] of known energy levels of

[9] C. Li, Phys. Rev. **88**, 1038 (1952).
[10] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).
[11] Reilly, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. **86**, 857 (1952), and references.
[12] H. F. Stoddard and H. E. Gove, Phys. Rev. **87**, 262 (1952), and references.

Al^{27} below 6 Mev, it is clear that absorption techniques are not likely to be adequate to establish the decay scheme from the highly excited states produced by proton capture in Mg^{26}.

Casson[13] has measured the gamma-ray energies at the 336- and 314-kev resonances with a scintillation spectrometer. At the 336-kev resonance he found 5.8- and 2.8-Mev gamma rays, while the gamma rays from the 314-kev resonance had an energy of about 4.3 Mev. Our measurement at the 450-kev level indicated a 6.0-Mev gamma ray, a value in good agreement with the 6.2 Mev reported by Tangen.[3] These values are compatible with the possibility of an initial transition to the well-known 2.8-Mev level.

[13] H. Casson, Phys. Rev. **89**, 809 (1953).

V. ACKNOWLEDGMENTS

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Decay Scheme of Co^{56}

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The decay scheme of Co^{56} was studied by means of a magnetic lens spectrometer and a gamma-gamma coincidence scintillation spectrometer. The positron spectrum consists of two groups of maximum energies of 1.50 Mev and 0.44 Mev, relative abundance of 96 percent and 4 percent, respectively, leading to a second and third excited state of Fe^{56}. Orbital electron capture also takes place involving several other excited states. Both of the beta-ray spectra involved appear to have the "allowed" shape of the Fermi plot. The energies of the gamma rays emitted by the Fe^{56} nucleus were determined by studies of the photoelectron spectrum and scintillation spectrum. The energies determined were 0.845 Mev, 1.24 Mev, 1.75 Mev, 2.30 Mev, 2.60 Mev, and 3.25 Mev, respectively. These gamma rays were fitted into the decay scheme by means of beta spectrum analysis and gamma-gamma coincidence experiments.

INTRODUCTION

IT was first reported by Livingood and Seaborg[1] that Co^{56} had a half-life of about 72 days. Cook and McDaniel,[2] using absorption and coincidence methods, reported that the disintegration took place by K capture and a single positron emission with an upper energy limit of 1.20 Mev. The average energy for the several gamma rays present was 1.74 Mev. Elliott and Deutsch[3] using a magnetic lens spectrometer and coincidence methods, reported a positron spectrum of a maximum energy of 1.50 Mev; they found the Fermi plot to be a straight line down to 0.48 Mev. The presence of the other cobalt isotopes prevented the investigation of the spectrum beyond this point. Six gamma rays ranging in energy from 0.845 Mev to 3.25 Mev were also reported.

In the present work the aim was to study Co^{56} without interference from Co^{57} and Co^{58}. For this purpose, a sample of ferric oxide enriched in Fe^{56} (99.84 percent) was obtained from Oak Ridge National Laboratory and bombarded in the cyclotron of the University of California. The target was under bombardment by 10-Mev protons for six hours, the protons being accelerated as hydrogen molecule ions. The total irradiation was 28 microampere hours. A carrier-free sample of Co^{56} was obtained and its mode of decay was studied by both a magnetic lens type spectrometer and a gamma-gamma coincidence scintillation spectrometer.

[1] J. J. Livengood and G. T. Seaborg, Phys. Rev. **60**, 913 (1941).
[2] C. S. Cook and P. W. McDaniel, Phys. Rev. **62**, 412 (1942).
[3] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943).

SOURCE PREPARATION

The bombarded ferric oxide was dissovled in $6N$ hydrochloric acid and treated with a few drops of bromine water, the latter acting as an oxidizing agent for the iron. The solution was evaporated to dryness and the residue dissolved in $6N$ hydrochloric acid. The solution was cooled to 5 degrees centigrade and transferred to a separatory funnel along with an equal volume of chilled ether. The two phases were shaken together and the aqueous phase containing the radioactive cobalt and some iron was extracted. The aqueous phase was then evaporated almost to dryness, diluted to 25 ml with triple distilled water, and the pH adjusted to 1.5. The solution was gently heated, then dilute ammonium hydroxide was added until the pH was approximately 4.5. After allowing 2 hours for the hydrous ferric oxide to settle, the solution was filtered, evaporated to dryness, and the ammonium chloride sublimed. The small residue remaining was dissolved in 1 ml of $0.01N$ hydrochloric acid and ammonium hydroxide added until the pH of the solution was ap-